DOCUMENT RESUME

ED 275 721 TM 860 635

AUTHOR	Keele, Steven W.; And Others
TITLE	Force Control and Its Relation to Timing. Cognitive Science Program, Technical Report No. 86-4.
INSTITUTION	Oregon Univ., Eugene. Dept. of Psychology.
SPONS AGENCY	National Science Foundation, Washington, D.C.; Office of Naval Research, Arlington, Va. Personnel and Training Research Programs Office.
REPORT NO	ONR-86-4
PUB DATE	1 May 86
CONTRACT	N00014-83-K-0601
GRANT	BNS8119274
NOTE	22p.
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	Adults; *Cognitive Processes; *Conceptual Tempo; Correlation; *Force; Higher Education; Interaction; *Motor Reactions; *Perceptual Motor Coordination; Psychomotor Skills; Reaction Time; Time Management
IDENTIFIERS	Tapping Test; *Timing

ABSTRACT

Timing and speed are suggested to be the two general factors of coordination that differentiate people across a variety of motor movements. This study provides evidence for a third general factor of coordination, that of force control. Subjects that exhibit low variability in reproducing a target force with one effector, such as the finger, show low variability with other effectors, foot or forearm. In addition, ability in force control cuts across different force ranges and across situations where force is either the primary goal or of secondary importance. Force records obtained during a periodic tapping task show that, although force control is largely independent of timing, there are some interactions between the two factors. Force variation appears to slightly distort timing in part because large forces speed up implementation of movement, thereby shortening preceding intervals and lengthening following ones, and in part because force variation alters central timing mechanisms. (Author/JAZ)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED275727

Cognitive Science Program

FUGE CONTROL AND ITS RELATION TO TIPPING

BY

STEVEN M. WEISS, HOWARD L. TWEED,
ROBERT A. FOLLERT

Technical Report No. 86-4

University of Oregon

Research Sponsored by:

Personnel and Training Research Programs
Psychological Sciences Division
Office of Naval Research
Under Contract No. N00014-83-K-0601
Work Unit No. NR 667-464

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

X This document has been reproduced as received from the person or organization originating it.

☐ Minor changes have been made to improve reproduction quality.

• Points of view or opinions stated in this document do not necessarily represent official OERI position or policy.

BEST COPY AVAILABLE

Reproduction in whole or in part is permitted for any purpose of the United States Government.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ONR No. 86-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FORCE CONTROL AND ITS RELATION TO TIMING		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Steven W. Keele, Richard I. Ivry and Robert A. Pokorny		8. CONTRACT OR GRANT NUMBER(s) N00014-83-K-0601
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Psychology University of Oregon		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 667-523
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE May 1, 1986 13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Components of coordination, force, force control, force variability, timing, rhythm, accents

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Previous work (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985) suggested two general factors of coordination that differentiate people across a variety of motor movements, factors of timing and speed. This study provides comparable evidence for a third general factor of coordination, that of force control. Subjects that exhibit low variability in reporducing a target force with one effector, such as the finger, show low variability with other effectors, foot or forearm. In addition, ability in force control cuts across different force ranges and across situations where force is either the primary

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102 LF 014 6601

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (cont.)

goal or of secondary importance. Force records obtained during a periodic tapping task show that, although force control is largely independent of timing, there are some interactions between the two factors. Force variation appears to slightly distort timing in part because large forces speed up implementation of movement, thereby shortening preceding intervals and lengthening following ones, and in part because force variation alters central timing mechanisms.

Force Control and Its Relation to Timing (1)

Steven W. Keele, Richard I. Ivry, and Robert A. Pokorny

University of Oregon

Do people differ from one another in general factors of coordination? In previous work (Keele & Hawkins, 1982 and Keele, Pokorny, Corcos, & Ivry, 1985) we suggested that speed control and timing control might be two general factors of coordination. In this study we investigate a similar issue with respect to force control. In addition, the interaction between force control and timing control is examined.

While it appears intuitively clear that some people are more coordinated than others, little research has supported such a view. In an analysis of much literature devoted to the problem, Martenuik (1974) concluded that success on one skill seems not to predict success on another. Moreover, there is little evidence that specific underlying abilities predict skill. A similar viewpoint emerged from factor analytic work by Fleishman (1966), which showed that as people become more skilled, task specific factors become more important and general factors decline in importance. The view that coordination is task specific is congenial to conclusions arising from the analysis of many cognitive skills. It has been argued, for example, that chess skill (Chase and Simon, 1973) and memory skill (Ericcson and Chase, 1982) arise largely from extensive learning in which the player acquires a huge repetoire of recognizable patterns. In the motor domain, Allard, Graham, and Paarsalu (1980) found that more advanced basketball players have acquired specialized knowledge about particular patterns that allow them to more easily encode positions of the players around them.

Despite the clear evidence that specific knowledge gained from practice is of paramount importance in skill, still it is possible that general coordination factors constrain the degree of skill attainable with high levels of practice. Our previous work suggested that speed of repetitive movement and precision of motor and perceptual timing are such general factors. Keele and Hawkins (1982) reported that the maximum speed at which one can repetitively tap is correlated at .5 or more across such diverse effectors as finger, thumb, wrist, forearm, and foot. Keele, Pokorny, Corcos, and Ivry (1985) showed that motor timing accuracy correlated across finger and foot. Moreover, motor timing in tapping correlates with the ability to judge the durations of intervals between brief perceptual events, suggesting that timing ability is at least partly common to production and perception.

These factors of speed and timing may constrain the ultimate level of performance in highly practiced skills. Book (1924) found that champion typists could tap repetitively considerably faster than control subjects, even when muscle groups minimally involved in typing are used. He also demonstrated a correlation between tapping speed and attained speed in a college typing course. Importantly, experience in typing did not itself increase tapping speed. In our own work (Keele, et. al., 1985), professional pianists were significantly faster in finger tapping, less variable in timing of both finger and foot, and more acute in judging the relative durations of perceptual events than were non-pianist control subjects.

This study investigates a third factor of coordination, force control. One question is whether the ability to control force is related across different effectors, in this case index finger, forearm, and foot. People are asked to produce a given force on a force key with one of the effectors. After a few force pulses with feedback, they are asked to produce several more

pulses of the same force without feedback. The variability of the peak forces over the pulses without feedback constitutes the measure of force control. Thus, the question reduces to whether the variability of force correlates across effectors. Positive evidence would provide support for a general factor of force control.

A second question concerns the inter-relation of force, speed, and time. In our previous work (Keele, et. al, 1985), we postulated that one factor that would influence maximum speed is timing variability. To move back and forth at the fastest speed requires that signals to the agonist and antagonist muscles be perfectly phased. Any variation in timing would slow the rate of movement below that attainable with perfect timing. In accordance with that prediction, we found that inter-tap variability during paced tapping, which is a measure of timing variance, correlated with the maximum speed of tapping. It appears therefore, that speed and timing are inter-related factors. This study investigates whether force control and timing also are inter-related.

Suppose that while attempting to tap at even time intervals there is some random variation in force. If by chance a particular tap was performed with larger than normal force, the effector, say the finger, might travel more rapidly and the tapping key would be pressed early. This random variation in force would tend to shorten the preceding time interval. Assuming that the central timing of the next tap is unaltered, this higher than normal force would also lengthen the following interval. In other words, there should be a negative correlation between force on an individual tap and the length of the interval that precedes it and a positive correlation between force and the length of the following interval. The first experiment of this study includes a condition in which the subjects' task is to produce timed taps without having a partiular force target. The force of every tap is measured in order to correlate forces of individual taps with preceding and following time intervals.

If indeed force variation is correlated with timing variation on a tap-by-tap analysis, then one would expect that people that are more variable in force control would also tend to be more variable in timing. This prediction is tested by correlating the overall degree of force variation during timed tapping with the timing variation. This is a more macro-level analysis of the relation between force and timing than the tap-by-tap analysis. In the situation where subjects attempt to produce particular forces, timing is not crucial. People produce force pulses in response to a non-periodic signal. In addition to examining whether such "untimed" force variation of one effector correlates with force variation of another effector, we also tested whether untimed force variation correlates with timed force variation to further explore the generality of force control. These issues are all examined in the first two experiments.

The third experiment examines a second facet of the interaction between force and time. Whereas in the first study the influence of random variations in force and their effect on timing is studied, the third study investigates how deliberate alterations in force of a movement affects the timing of movement. Subjects are asked to tap a rhythm in which periodic taps are accented with a heavier force. The question of interest is whether such force alterations also alter timing.

Experiment 1

Subjects in this study performed three different tasks, each with their forefinger and their forearm. One task, which we call untimed force, involved producing target forces in response to an auditory signal by pressing on a button connected to a strain gauge. The second task, called timed force, involved responding on the same apparatus in synchrony with a pace tone that occurred every 400 msec. After synchronization, the pace tone disappeared and the subject

attempted to press the response button at the same pace. The onset times of the presses were used to determine the degree of timing variability. In addition the maximum force of each press was recorded to determine timed force variability. The third task required the subjects to repetitively press a key as rapidly as possible to determine their maximum speed. Correlating performance on each task between finger and forearm yields an indication of whether force control, timing control, and speed are general factors of coordination. Correlating performance between tasks assesses the interaction of the three factors.

Methods

Subjects

Twenty-nine young, right-handed adults were paid to serve in two sessions of the experiment.

Apparatus and procedure

In the untimed force condition subjects made isometric presses on a button (1.5 cm. diameter) that was connected to a strain gauge (Grass Model FT100 force transducer). Presses were made with either the right forefinger or the right forearm. For finger presses the tip of the finger rested lightly on the key. When subjects heard a tone, they produced a force pulse with a single flexion-extension movement of the extended forefinger. For forearm movements the subject curled the fingers into a half-closed fist and rotated the wrist so that the lateral surface of the metacarpophalangeal joint rested on the key. The subject made pressing movements by a slight extension-flexion pulse of the forearm about the elbow. A horizontal line on an oscilloscope screen signified one of five target forces of 3.0, 5.1, 7.0, 9.6, and 10.8 newtons (corresponding to masses of 310, 525, 720, 980, and 1100 grams). At the sound of a tone, subjects made a single force pulse. A vertical line with height proportional to the produced force was then shown on the screen. An accurate force would show the vertical line terminating on the horizontal target line. After six such force pulses, the feedback and horizontal target line were removed for six remaining pulses for which the subject attempted to produce the target force. During this phase, an interval of either 750, 1000, or 1250 msec. transpired between one response and the next tone. Randomization of interval was provided to prevent the subject from getting into a rhythm of presses. The standard deviation of force produced when feedback was absent was the primary dependent measure. There were 10 bouts of six pulses of each target force for each effector distributed over the two sessions.

In the timed force task a pacing tone occurred every 400 msec. Subjects pressed the key in the same manner as for the untimed force task, but in this case they attempted to synchornize the press with the tone. The tone ceased after 12 taps, and the subject continued to tap out the target interval for 30 more taps. The standard deviation of the intertap interval was the primary measure of timing precision. Although subjects were not instructed to use any particular amount of force other than staying within the bounds of the strain guage, which accepted a maximum force of 14 newtons, the force on each tap was also measured. The standard deviation of the force over the 30 taps without the pacing tone is called timed force variability. Over the two sessions each subject produced 30 such trials of 30 taps each with both finger and forearm.

In the third task, subjects tapped as rapidly as possible on a microswitch key with either their finger or their forearm for bouts of 4 seconds. In this case the finger or side of the hand was kept in contact with the key, but the key traveled a short distance of 1.5 mm, and it made a barely audible click and a distinct tactual feel each time it was pressed. Over the two

sessions, each subject had 12 bouts of speeded taps for each of finger and forearm (two additional bouts during each session served as warmup).

The order of the three tasks was counterbalanced across days, but the order was the same for each subject to ensure that differences in performance of subjects across tasks were not due to differences in test order.

Results and Discussion

Force Control

The primary interest in this study is in the correlations among the various dependent variables. However, it is of subsidiary interest to know how force variability depends on target force. Work by Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) showed a linear relation between the standard deviation of forces produced and the target force being attempted. Figure 1 shows the relation between standard deviation of force and target force for the untimed force condition of this study. As in the Schmidt, et. al. study there is a reasonably linear relation between the two variables.

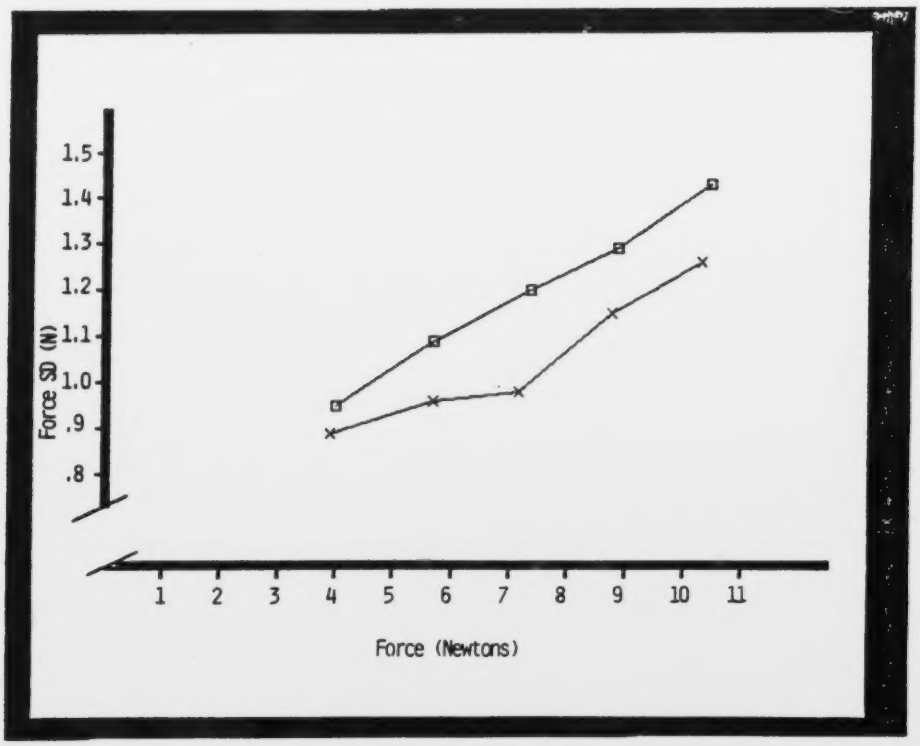

Figure 1: The relation between the standard deviation of produced forces and the mean produced force for five different target values and for finger (Xs) and forearm (boxes).

Table 1 shows the correlations of primary interest from this study. The variability of timing, variability of timed and untimed force, and the mean intertap interval in the speed task were averaged over data from both sessions for each effector, finger and forearm, and for each subject. Also, the standard deviations for the five force targets were averaged. These mean scores were then correlated across the 29 subjects. For 29 subjects, correlations above .32 are significant by a 1-tailed test at the .05 level of confidence; correlations above .38 are significant at the .025 level.

TABLE 1

CORRELATIONS AMONG SPEED, TIME AND FORCE

		TIMING VARIABILITY		SPEED		UNTIMED FORCE		TIMED FORCE	
		FINGER	ARM	FINGER	ARM	FINGER	ARM	FINGER	ARM
TIMING VAR	FINGER	.92							
	ARM	.90	.91						
SPEED	FINGER	.20	.31	.88					
	ARM	.11	.24	.69	.95				
UNTIMED FORCE	FINGER	.30	.34	.10	.26	.87			
	ARM	.18	.21	.00	.09	.76	.76		
TIMED FORCE	FINGER	.35	.43	.11	.04	.39	.42	.68	
	ARM	.37	.42	-.06	-.21	.40	.33	.76	.82

NOTES: $r > .32$, $p < .05$
$r > .38$, $p < .01$
Underlined values are reliabilities

Consider first the correlations among the different conditions of force control. The correlation between untimed force variability of the finger with that of the forearm is .76. An identical value is found for timed force between finger and forearm. Timed and untimed force variability correlate with each other about .4 in the different combinations. If force variability is averaged over finger and forearm, the timed and untimed force variability correlated .43 (not shown in Table 1). Taken together these correlations suggest considerable

commonality in force control across effector and across conditions in which force is produced. As such, force control appears to be a factor of coordination on which people differ.

A potential problem to consider in assessing the correlations among the force variability scores is whether they might be explained by some differential strategy across subjects. One possibility is that some people may have a faster onset of force than others and perhaps that would affect variability of peak force, the primary measure of interest. For untimed force there were negligible and non-significant correlations ranging from -.05 to -.20 between time to peak force and variability of peak force for various combinations of finger and forearm. Thus, for untimed force, the correlation between force variablities of finger and forearm cannot be explained by different strategies across subjects in time to peak force. For timed force, however, when data of finger and forearm are averaged, time to peak force correlates .49 with variability of force. This correlation, while sizeable, is not as large as the .76 correlation between force variabilities of finger and forearm. Thus in both the timed and untimed tasks, the force variablilty correlations cannot be accounted for, at least in their entirety, by differences among subjects in time to peak force.

Relation of Force Control to Timing

Consistent with the work of Keele, et. al., (1985), timing control correlates across effectors. In the timing condition of this study, subjects pressed on the response key at regular intervals. The measure of timing variability was the standard deviation, averaged over sessions, of the inter-tap intervals taken from those periods after cessation of the pace tone. Table 1 shows the correlation between finger and forearm timing to be .90, a figure considerably higher than between finger and foot timing, which was about .45 in the Keele, et. al. study. Taken together, the two studies suggest considerable commanality among the timing mechanisms of differing effectors.

One factor that could influence the variability of inter-tap intervals is variation in force. A larger force command from the central nervous system might actuate the muscles more rapidly than a smaller force command, resulting in variation in the time of actual key press. It would be expected, therefore, that people with larger force variation would also show larger time variation. Table
1 shows moderate correlations of about .4 between timing variation and force variation in the timing task, giving support to the prediction. However, variation of force in the untimed condition fails to correlate significantly with timing variation in the timed condition.

The relation between force and timing can also be examined by relating tap-to-tap variations of force with tap-to-tap variations in interval length. Figure 2 shows the correlation between force of a tap and interval lengths that occur before or after by tap by varying amounts. Lag 0 corresponds to the correlation between force of a particular tap and the interval just preceding it. Negative lags concern correlations between force of the tap and ealier intervals, and positive lags concern the relation between the force of a tap and later intervals. The correlations for both negative lags and positive lags beyond 1 are near zero, but there is a small correlation of about -.10 between force and time at lag 0 and a correlation of .15 at lag 1. This pattern is as predicted but the correlations are extremely small. Momentary variations in force account for only about 1-2% of the momentary variations in time. Despite their small size, the correlations, are reliable because of the fact that they are based on 900 taps per subject for each of finger and forearm and averaged over 29 subjects.

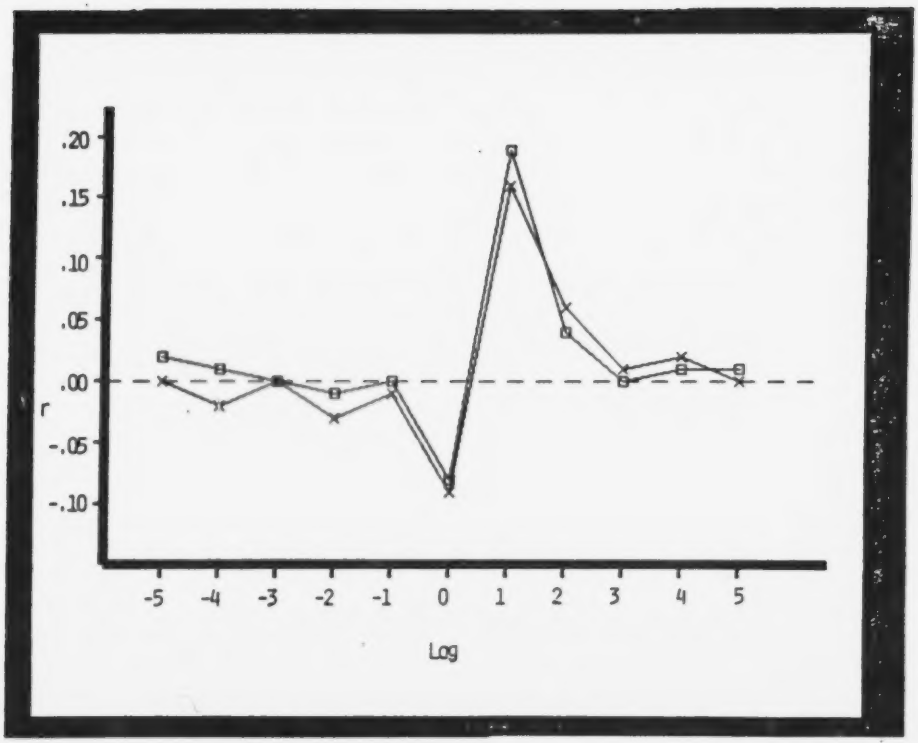

Figure 2: Correlation of individual tap forces with the duration of the preceding and following intertap intervals. Lag 0 corresponds to the correlation between tap force and the duration of the interval terminated by onset of that tap. Lag 1 corresponds to the relation between force and the interval initiated by that force tap. Xs are for the finger and boxes for the forearm.

There is an apparent discrepancy between the magnitude of the correlations in the tap-to-tap analysis and the relation of overall force variation in the timing task to timing variation. The latter is considerably larger than the former. One reason for this is revealed in Figure 3. This figure shows the autocorrelation function of force of taps separated by varying numbers of intervening taps. The lag 1 autocorrelation refers to the correlation of forces of adjacent taps; lag 2 refers to the correlation of the forces of taps separated by one intervening tap; and so on. This figure shows sizeable correlations between successive forces--i.e., if one tap involves relatively large force, then following ones tend to be large also. This lack of independence of successive forces would tend to reduce the correlation of force with adjacent time intervals as portrayed in Figure 2.

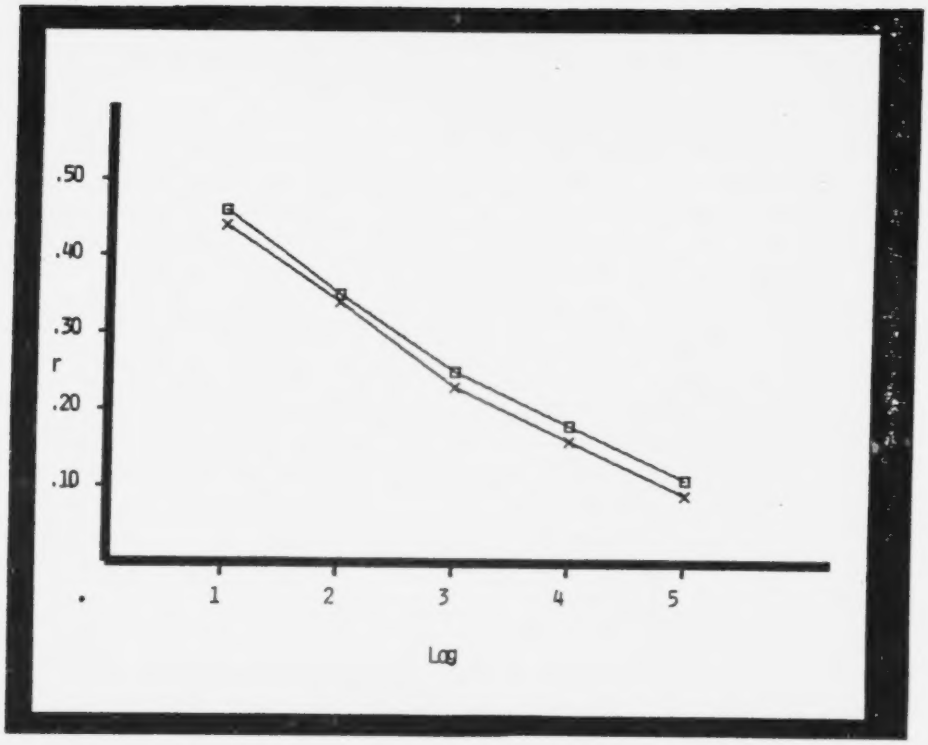

Figure 3: Autocorrelation function of the force of successive taps. The lag 1 correlation portrays the relation between the magnitude of one force pulse and the magnitude of the next force pulse. The lag 2 correlation is between forces separated by two intervening intervals. Xs are for the finger and boxes for the forearm.

A final analysis on the relation between force variation and timing variation made use of a theory of timing developed by Wing (1980) and Wing and Kristofferson (1973). The theory postulates that variance of intertap intervals comes from the additive influence of two separable sources. One source is variance in a clock, and the other source is variance in the duration of implementing a movement once the timer gives the command to move. The theory implies that while both clock and implementation influence total variance in timing, variance in implementation time also introduces a negative correlation in the duration of successive inter-tap intervals (c.f., Wing, 1980 for details of the model and a summary of data favoring the theory). The magnitude of the covariance of successive intervals serves as an estimator of the implementation time variance. Because implementation variance and clock variance sum to produce total variance of the inter-tap intervals, clock variance can be estimated by subtracting the implementation variance from the total variance.

If the magnitude of force affects implementation time, with large forces activating the musculature faster than smaller forces, then one would expect that when timing variance is decomposed into clock and motor delay variance, the magnitude of force variation across different people would correlate with the magnitude of implementation variance rather than with clock variance. To test this prediction, force and timing variances were first averaged over finger and forearm and force. Contrary to the expectation, force variation in the timed task correlates more highly with clock variance ($r = .47$) than with implementation variance ($r = -.08$). One reason for this outcome may be that force variance is small compared to the total force range that muscles are capable of producing. Such small variations may produce virtually

no differences in muscular activation times. Why then would force variation correlate with clock variance? The analysis of a Parkinsonian patient (Wing, Keele, and Margolin, 1984), who presumably has basal ganglia damage, revealed an increase in clock variance rather than implementation variance. Some researchers have postulated that Parkisonian deficits also manifest themselves as deficits of force control (e.g., Hallett & Koshbin, 1980). One possiblity to explain the present results, therefore, is that the clock mechanism is part of an internal circuit in which force must be programmed (but not implemented) before the next round of the clock circuit is initiated. That is, prior to emitting a motor command both force and time must be prepared. Variation in the time to program either one will show up as variation in the pre-implementation period and be manifested as clock variance. This study does not measure variation in duration to program force and instead measures force variation itself. We might nonetheless speculate that the two factors are intimately related. A second possible explanation of the correlation between clock and force variabilities is that the duration of force buildup may be determined by a timing mechanism. Hence any variation in timing may be a factor in variation of force achieved.

Relation of Timing and Force Control to Speed

In earlier studies (Keele & Hawkins, 1982 and Keele, et. al., 1985) it was found the maximum speed at which people could repetitively move was correlated across different effectors. That observation is confirmed here: Mean inter-tap interval at maximum speed is correlated across subjects between finger and forearm at .69 (see Table 1). The Keele, et. al. study also found that timing variation was correlated with maximum speed. People that were more variable tended to be slower in their maximum speed. An explanation of the result is that as one approaches maximum speed at which the muscles can be contracted, any mistiming of the onsets and offsets of the agonist and antagonist muscle activity will cause the reciprocation rate to be less than what could be achieved with perfect timing. Though the correlations between speed and timing in this study are in the correct direction, they are small and not statistically different from zero. The relation between speed and timing could use further replication. Also, in this study there are no significant correlations between speed and force control.

Summary

The ability to control force with finger movement is correlated with the ability to control force with forearm movement. Moreover, force control when such control is the object of intent correlates with variations in force when timing control is primary and force control is incidental. These observations suggest that a factor of force control, general to more than one effector, differentiates people. By and large these results are not explicable on the basis of strategic differences in either duration of a force pulse or the rate in which peak force is achieved.

People also differ from one another in their precision of timing repetitive movements. One minor factor that influences timing precision is force variation. People that are more variable in force during a timing task also tend to be more variable in timing. This relation is largely one between a clock compenent of timing and force control. However, a micro-analysis of tap-to-tap forces and times suggests that there is also a very small relation between force variation and the variation in implementation component of timing such that a randomly large force tends to shorten the preceding interval and lengthen the following interval. The reverse is true for small forces.

People also differ from one another in their precision of timing repetitive movements. One minor factor that influences timing precision is force variation. People that are more variable in force during a timing task also tend to be more variable in timing. This relation is largely one between a clock compenent of timing and force control. However, a micro-analysis of tap-to-tap forces and times suggests that there is also a very small relation between force variation and the variation in implementation component of timing such that a randomly large force tends to shorten the preceding interval and lengthen the following interval. The reverse is true for small forces.

Experiment 2

The first experiment showed that variability of force control was correlated between forefinger and forearm. Regardless of which effector was used, the same force levels were required. The second experiment explores the generality of a force control factor. Subjects in this experiment produced untimed force pulses with either the forefinger or the foot. The force range for the foot was considerably higher than for the finger. A substantial correlation between variability of force production with one effector and the other, even with different force ranges, would suggest rather wide generality of force control.

Method

Subjects

Twenty-nine right-handed young adults from the University of Oregon subject pool were paid to participate in the experiment. None had participated in Experiment 1.

Apparatus and procedure

The same apparatus and procedure as used for the force measurement portion of Experiment 1 was used. The force targets for the forefinger were 5.1, 6.1, 7.0, and 7.8 newtons. For the foot, the target forces were 14.7, 16.9, 19.2, and 21.1 newtons. For the forefinger the presses were made as before with the tip of the finger always in contact with the isometric force key. For the forefoot, subjects wore socks and rested the balls of their feet on the force key. For each effector subjects made six responses per trial with feedback followed by six responses without feedback. There were five trials for each target force in each of two sessions.

Results and Discussion

The standard deviations of force for the six force pulses without feedback of a given trial were averaged over all force levels and all trials of both days for both the finger and the foot. For the finger the force variability averaged over all subjects was 1.5 newtons; for the foot it was 4.9 newtons. The correlation of variability of the foot with variability of the finger across subjects was .73, a value near that found between finger and forearm in Experiment 1. The reliability of force variability for the finger was .91 and for the foot it was .89.

The results of Experiment 2 extend the conclusions of Experiment 1 in suggesting a factor of force control that is rather general. People that are relatively good at producing the same force on repeated occasions with one effector tend quite strongly to be good with another effector. Experiment 1 found such to be the case comparing finger and forearm, and the second experiment found similar results comparing finger and foot. Second, such force control appears

general across a considerable range of force. In Experiment 1 the force range for finger and for forearm were equal. The force range was small, requiring rather delicate control for the forearm compared to the finger, given the much greater strength and mass of the forearm. Nonetheless, subjects' abilities to control force were highly correlated across effector. In the second experiment the force requirements were different for foot and finger, being considerably higher for the foot, but perhaps more comparable in relation to strength of the two effectors. Again, subjects' abilities correlated highly across the effectors.

Experiment 3

Experiment 1 found small to modest correlations between force variation and timing variation in a situation where constant timing was the primary goal. The purpose of the third experiment was to examine the influence of deliberate alterations in force, made to accent periodic taps, on timing variation. Such deliberate force alterations are larger in magnitude than chance variation in force and may, therefore, result in a larger interaction between force control and timing. Subjects were instructed to repetitively tap out a pattern of two short intervals followed by an interval that was twice as long. Subjects were instructed to produce an accent at one of the three tap positions within each cycle of the pattern by making a stronger press on the force key. In a fourth condition, subjects attempted to produce an unaccented pattern by responding with equal force at each position. The question of interest concerned how accent position influenced interval duration. If the effect of increased force is to shorten the duration from the central emission of the command to press to the onset of the press, then it would be expected that an accent would decrease the duration of the preceding interval, since the response would occur relatively early, and increase the length of the following interval. As will be seen, however, the relation between timing and force is more complicated.

This experiment is essentially a replication of an unpublished thesis by Greim (1983), with the only notable difference that in this study subjects made isometric responses on a force key, rather than moving their fingers, and the forces of the actual pulses were measured.

Method

Subjects

The subjects were 12 young adults drawn from the Cognitive Lab Subject Pool at the University of Oregon and paid for their participation.

Apparatus and procedure

The basic apparatus was the same force transducer as in the first two studies. All responses were made with the right hand. Subjects sat with their forearm and palm resting on a platform and the tip of their index finger on the button atop the force transducer. At the beginning of a condition the subjects were informed which position in the pattern was to be accented. They then listened to a temporal pattern of 50 msec. duration clicks. The intervals between onsets of successive clicks were 400, 400, and 800 msec. in each cycle and the accented click was played at a louder volume. The three intervals cycled repetitively for a total of five times. Subjects synchronized finger presses on the force key with the clicks, making a more forceful press, not to exceed 9.8 newtons, for the accented position. After the fifth cycle of synchronization, the clicks disappeared and subjects continued to tap the intervals without reference to the pace signals for another 10 cycles, ending with the long interval (the last

interval was excluded from data analysis). Feedback , which was provided at the end of each trial, conveyed the average force produced at each interval and number, if any, of responses which exceeded the allowable force of 9.8 newtons. No timing feedback was provided, since we didn't want subjects to adopt strategies of adjusting times based on feedback.

Altogether there were four accent conditions. Five good trials were obtained for each condition on each of four runs. Trials in which a produced interval differed from the target by plus or minus 50% were rerun. The four bouts of the four conditions were counterbalanced by a four by four latin square design over the course of a session, and the order of conditions was also counterbalanced across subjects, also with a latin square design. The experimental session took one to one and a half hours and altogether involved 20 bouts of 10 cycles through the pattern for each condition and each subject.

The four accent conditions required the subject to 1) attempt to make each press the same in force, 2) make the presses at the end of the long intervals more forcefully than the others, 3) make the presses after the first of the short intervals more forcefully, and 4) make the presses that divided the short intervals more forcefully. The only restrictions on force other than that the desired one be made more forcefully was that no press could be more than 9.8 newtons.

Results and Discussion

Before examining the effects of accent position on intertap intervals, it first is useful to present evidence that accents varied by condition. Table 2 shows the mean peak force with which the force key was pressed as a function of accent position. The control condition showed little variation in force with tap position as would be expected given instructions to produce each tap as evenly as possible. The other three conditions showed the accented position to receive a higher force. The unaccented positions showed about the same force as in the control condition. Every one of the 12 subjects showed the pattern exhibited in the means with one exception: One subject failed to produce more force on the accent position that fell between the two 400 msec target intervals.

Table 2: Peak forces, key press durations, time to peak force, and ratio of time to peak force to key press duration (Experiment 3)

	No Accent			Accent 1			Accent 2			Accent 3		
Target Interval	400	400	800	400	400	800	400	400	800	400	400	800
Force Newtons	4.6	4.4	4.8	8.6	4.5	4.3	4.6	8.6	5.3	4.4	4.2	8.8
Press Duration Msec	182	178	187	235	176	178	176	220	193	175	165	245
Time to Peak Force Msec	79	75	80	106	74	74	76	95	82	76	71	107
Peak Time/Duration Ratio	.43	.42	.43	.45	.42	.42	.43	.43	.43	.43	.43	.43

Although subjects were instructed to make accents with larger force pulses, it also turned out that the accented position received a longer duration force pulse. Again, every subject showed the effect except for the one subject who failed to produce a stronger force in the intended position when the accent was to split the two short intervals. The mean press durations are also shown in Table 2, where it is apparent that the mean pulse durations in the unaccented position were all about the same as in the control. Another measure, which will play a role in subsequent interpretations, is the time from the beginning of the force pulse to reach maximum force. The mean results appear in Table 2 where they are seen to mimic the effects of pulse duration: It takes longer to reach peak force the larger the force applied. The last row of Table 2 shows the ratio of the time to reach peak force to the total press time. The ratio is remarkably constant across conditions, being about .42.

The question of primary interest concerns the effects of accent position on the intertap intervals. The expectation was that an accented tap would lead to a shorter than normal preceding interval and a longer than normal following interval. The data presented in the top two rows of Table 3 show such to be the case in two accent conditions, but only marginally in the third condition in which the accent preceded the long interval. The top row shows the mean intertap intervals averaged over all subjects. If a total tap cycle were veridical in time, it would take 1600 msec. However, on the average some of the conditions took slightly more than 1600 msec on average and some took slightly less. To facilitate comparison of conditions, the second row shows standardized intertap intervals with each interval adjusted proportionately to achieve a total cycle time of 1600 msec. All statistical tests are based on the standardized intervals.

Table 3: Mean onset-to-onset intertap intervals (unadjusted for cycle length), standardized intertap intervals (adjusted for cycle length), mean peak force-to-peak force intertap intervals (unadjusted), and peak-to-peak standardized intervals. All in msec. (Experiment 3.)

	No Accent			Accent 1			Accent 2			Accent 3		
Target Interval	400	400	800	400	400	800	400	400	800	400	400	800
Mean Interval	400	398	811	448	398	748	392	427	796	387	389	800
Standardized Interval	398	396	806	450	399	751	388	423	789	393	395	812
Peak-to-Peak Interval	396	403	810	416	398	780	411	414	790	382	425	769
Peak-to-Peak Standardized Interval	394	401	805	418	399	783	407	410	783	388	431	781

Note: For accent 1 the accented press ends the 800 msec interval and starts the first 400 msec interval. For accent 2 the accented press divides the two 400 msec intervals. For accent 3 the accented press divides ends the second 400 msec interval and starts the 800 msec interval.

When the accent falls on the taps that close the long interval and begin the first short interval (condition 2), the long interval is shortened and the first short interval is lengthened beyond that for the control condition. Eleven of twelve subjects show both effects ($p < .01$ by a two-tailed binomial test). The one subject who does not is the subject mentioned above who did not produce the proper accenting in another condition. This subject produced an accent at the designated point in this condition, but the increase in force was considerably smaller than that of any other subject. The remaining interval shows little change from control to accent as might be expected since it is not bordered by an accent.

When the accent falls on the tap between the two short intervals (condition 3), the preceding interval again is shortened relative to the control condition but in this case for only 8 of 12 subjects ($p > .05$ by a binomial test, but $p < .05$ by a two-tailed t test). The following interval was lengthened for 10 of 12 subjects ($p < .05$). The remaining long interval, which was not bordered by an accent, nonetheless was shortened by 9 of 12 subjects.

The fourth condition in which the accent falls between the second short and the long intervals shows virtually no effect on the short interval and only a small one on the long interval. However, neither interval is significantly different from the control condition.

Overall it appears that accenting decreases the length of the preceding interval and increases the following one, although other effects seem to be operating because the general phenomenon is clearly found in only two of the three accent conditions. A possible reason for at least part of the shortening of the preceding interval and lengthening of the following interval is that when a central command is issued to press, the muscular forces are mobilized more rapidly the stronger the force. This would cause the press to be actuated sooner, shortening the preceding interval. If, however, the timing system is unaltered, then the command for the succeeding response would be given at its normal time, and assuming that the mobilization time for its response were normal, the interval since the onset of the last response would be increased since the last response had occurred early.

Although the onset of a more forceful movement may begin earlier, it is possible that the peak force is intended to occur at the target time. The data in Table 3 show that it takes longer to reach peak force for the larger accented forces. The intertap intervals can be recalculated to be based not on the onset-to-onset times but on peak-to-peak times. The mean intervals are shown in the third row of Table 4. Again, the mean duration of the total cycle time varies a bit from the target 1600 msec in the various conditions, so the fourth row of the table shows standardized scores with each interval adjusted proportionally so that the total adds to 1600 msec per cycle. For the first two accent conditions, there is some muting of the overall effect of accent when peak-to-peak intervals are compared to onset-to-onset intervals. This lends some credence to the view that part of the effect of increased force is to alter the duration of motor implementation. Still, residual effects of accent on peak-to-peak intervals suggest that not all the effect of accent can be explained by the mobilization time of the response. Futhermore, in the case of the accent at the end of the second short interval and the beginning of the long interval, a completely different result appears. Based on peak-to-peak intervals, the increased force increases the duration of the <u>preceding</u> interval and decreases the <u>following</u> one, an effect just the opposite of what would be expected by reponse mobilization speeds. The effects, when compared to the control, are statistically significant ($p < .05$).

The conclusion seems inescapable that accenting does more than just alter the speed of motor implementation. Accent also alters the underlying time structure of the sequence. However, the rules of alteration are not entirely clear to us. Sometimes the accent increases a

preceding interval and sometimes it decreases the interval, at least when intervals are measured from peak force to peak force.

The results of Experiment 3 basically confirm the results of Greim (1983). His study did not take actual force measurments and the response rate was somewhat quicker, involving a temporal pattern of 275, 275,and 550 msec. In addition, subjects in the Greim study moved their forefingers up and down on a key rather than isometrically pressing on a strain gauge as in the present experiment. Similar to the present results, he found an accented movement to be followed by a slightly longer than normal interval, but the preceding interval was only slightly if at all shorter than normal. Both the present results and the data of Greim are in contradiction to that of Semjen, Garcia-Colera, and Requin (1984). These authors found that an accent lengthened the preceding interval. The procedure of Semjen, et. al. differs in a couple of respects. Perhaps the most important difference is that their intertap intervals are much quicker than in the present studies, being 180 msec. Experiment 1 of this study and our previous work (Keele & Hawkins, 1982 and Keele, et. al., 1985) have shown the Semjen et. al. intervals to be very close to the maximum rate that people can tap. Weber, Blagowski, and Mankin (1982) have shown that when people speak sequences of letters or numbers as rapidly as possible, they slow down considerably when items must be alternately whispered and spoken aloud. It appears that changing the intensity parameter of a program takes considerable time. In the Semjen, et. al. study, accenting correponds to an intensity parameter change, and thus, when one taps nearly as fast as possible, implementing the change delays the next response. In line with this explanation Semjen, et. al. found the same effect, a lengthening of the interval preceding the accent, regardless of whether the accent was an increase or a decrease in force.

General Discussion

The current studies were concerned with two primary issues, one being the nature of individual differences in force control and the other being the interactions of force and time.

In previous work (Keele, et. al., 1985) we found subjects to differ from one another on basic timing control. Subjects regular at timing with one effector, such as the finger, tend to be regular with another, such as the foot. This was confirmed in Experiment 1 in which we compared finger and forearm. Moreover, in the earlier study (Keele et. al., 1985), we observed a significant correlation between motor timing and perceptual acuity in a temporal judgement task. Such results suggest that a basic factor of coordination is one of timing control. Further support of this conjecture was provided by the finding that highly skilled pianists are better on the timing measures than are non-pianists (Keele, et. al., 1985). In the current study, one goal was to determine whether a comparable factor of coordination was one of force control. The results suggest that such is the case. Individual differences in force control, measured as variabilty in producing a target force on several occasions, correlate across effectors of finger, forearm, and foot and across low and high force ranges. In addition, they correlate across situations in which force control is either primary or secondary to timing control. What we have not demonstrated, however, is whether or not this general factor of force control is an important aspect of coordination for various human skills.

The root cause of the correlations of force control across conditions can only be speculated about. They could be due to peripheral factors such as correlated muscle composition across the different motor effectors of individuals, due to central-peripheral factors such as innervation ratios of neurons to muscle fibers that are correlated across different effectors, or due to some central brain mechanism involved in force control. These issues remain for future research.

A second primary issue of this study concerned the relation between timing and force control. Are they completely independent factors? Our evidence suggests that they are separable factors but nonetheless that they interact. The correlations among the various force control situations of Experiments 1 and 2 and the correlations among the timing situations were substantially higher than those between force and timing. Still, when subjects attempt to produce periodic responses, there is modest correlation between variations in force and variations in time. Subjects less variable in force tend to be slightly less variable in timing. A running correlation between the force of individual key presses and the duration of preceding and following intervals also shows a tiny but systematic effect of force variation on time.

One possible model would be that a clock establishes the duration of movement intervals, then releases a movement implementation stage. Force specification would then be part of the implementation stage. Some aspects of Experiments 1 and 3 do suggest that larger forces are implemented faster than slower ones. In Experiment 1 the very small correlations between tap force and the durations of the preceding and following intervals are consistent with the view that larger forces are implemented faster than smaller forces. Likewise, there is a tendency in Experiment 3 for accented taps to shorten the preceding interval and lengthen the following one. However, not all the effects of force variation on timing seem relegated to an implementation stage. When the intertap intervals in Experiment 3 were measured from peak force to peak force rather than onset to onset, differing force accent positions still interacted with the magnitude of the intervals produced. Moreover, accent did not always shorten the preceding interval and lengthen the following one. These observations suggest that force is altering the basic temporal structure that occurs prior to implementation. Such results are consistent with another observation from Experiment 1. Recall that by a model of Wing (1980), the total variance of intertap intervals can be decomposed into clock variance and variance in motor implementation time. In Experiment 1 it was found that individual differences in force control correlated more highly with clock variance than with motor variance. These results are in agreement with the results of a study of a Parkinson patient with slow, weak movements (Wing, Keele, & Margolin, 1984). That patient, who presumably has difficulty providing sufficient force for normal movement, also exhibits a large increase in clock variance by the Wing model. In a preliminary report of a cerebellar patient (Keele, Manchester, & Rafal, 1985), we have speculated that in preparing a movement both time and force must be specified before the response is released and before another timing cycle begins. Thus, variances in both a timekeeper per se and in force preparation time may manifest themselves in a timing loop prior to actual movement implementation. It appears, therefore, that factors of force control and timing control are largely, but not entirely, independent. Force and time appear to have a modest interaction in both peripheral and central stages of motor production.

Footnote

This research was supported by a grant from the National Science Foundation (BNS8119274) to Steven Keele and to an Office of Naval Research contract (N00014-83-0601) to Michael Posner and Steven Keele. We also wish to thank Kathy Stanford, Ik Soo Moon, and David Greim for their aid on Experiments 1, 2, and 3 respectively.

References

Allard, F., Graham, S., & Paarsalu, M. E. (1980). Perception in sport: Basketball. Journal of Sport Psychology, 2, 14-21.

Book, W. F. (1924). Voluntary motor ability of the world's champion typists. Journal of Applied Psychology, 8, 283-308.

Chase, W. G. & Simon, H. A. (1973). The mind's eye in chess. In W G. Chase (Ed.) Visual information processing. New York: Academic Press.

Ericcson, K. A. & Chase, W. G. (1982). Exceptional memory. American Scientist, 70, 607-615.

Fleishman, E. A. (1966). Human abilities and the acquisition of skill. In E. A. Bilodeau (Ed.) Acquisition of skill. New York: Academic Press.

Greim, D. M. (1983). The effect of accent position on the reproduction of rhythmic patterns. Unpublished master's thesis. University of Oregon, Eugene, Oregon.

Hallett, M. & Khosbin, S. (1980). A physiological mechanism of bradykinesia. Brain, 101, 301-314.

Keele, S. W. & Hawkins, H. L. (1982). Explorations of individual differences relevant to high level skill. Journal of Motor Behavior 14, 3-23.

Keele, S. W., Manchester, D. L., & Rafal, R. D. (1985). Is the cerebellum involved in motor and perceptual timing: A case study. Unpublished tech. rept. #85-4, Cognitive Science Program, University of Oregon.

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. Acta Psychologica, 60, 173-191.

Marteniuk, R. G. (1974). Individual differences in motor performance and learning. In J. H. Wilmore (Ed.) Exercise and sports sciences review, Vol. 2. New York: Academic Press.

Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T., Jr. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. Psychological Review, 86, 415-451.

Semjen, A., Garcia-Colera, A., & Requin, J. (1984). On controlling force and time in rhythmic movement sequences: The effect of stress location. In J. Gibbon & L. Allan (Eds.) Timing and time perception. Annals of the New York Academy of Sciences, 423, 168-182.

Weber, R. J., Blagowsky, J., & Mankin, R. (1982). Switching time between overt and covert speech: Generative attention. Memory and Cognition, 10, 546-553.

Wing, A. M. (1980). The long and short of timing in motor sequences. In G. E. Stelmach and J. Requin (Eds.) Tutorials in motor behavior. Amsterdam: North Holland.

Wing, A. M., Keele, S. W., & Margolin, D. I. (1984). Motor disorder and the timing of repetitive movements. In J. Gibbon & L. Allan (Eds.) Timing and time perception. Annals of the New York Academy of Sciences, 423, 183-192.

Wing, A. M. & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. Perception and Psychophysics, 14, 5-12.